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FDS Modeling of the Sensitivity of the Smoke Potential Values used in Fire Safety Strategies

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ABSTRACT

To investigate the sensitivity of Fire Dynamics Simulator (FDS) with respect to the input parameters that are used to define the optical properties of the smoke, a parametric study was performed for relevant fire scenarios in an open plan office building. The parametric study mainly focuses on the two key parameters in FDS that define the optical properties of the smoke, namely the smoke potential and the effective heat of combustion.

In Denmark, the open source computational fluid dynamics (CFD) program Fire Dynamics Simulator is commonly used to assess the production and transport of the combustion products in performance based fire safety design. The results are used to evaluate the safety level of buildings based on the time comparison between the available safe egress time (ASET) and the required safe egress time (RSET). For a majority of performance based analysis the optical properties of the smoke determine the available safe egress time, as defined based on the acceptance visibility criterion defined in the Danish performance-based fire safety design code. Because there is no uniform test method to measure the optical properties of the smoke and due to the absence of a best practice guide that is widely accepted by the fire engineering community, values from a vast variety of experiments are used in the engineering analysis to express the properties that determine the decrease of visibility from the presence of smoke. The selection of these values, which are used as input parameters in the simulation model, determines to a great extent the results obtained using the CFD simulation tools, and thereby also the fire safety design.

As the majority of combustible materials in buildings are characterized by smoke potential values lower than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$, the underestimation of this input parameter may lead to the wrong assessment of the evacuation safety level of the building. In this context, in order to ensure a robust fire safety solution it is recommended that values around $1.0 - 2.0 \text{ ob}\cdot\text{m}^3/\text{g}$ are used to define the optical properties of the smoke in office building fires. Using these values to defining the design fires will reduce the sensitivity of the numerical fire simulation and further reduce the risk of overestimating the evacuation safety level (ESL) of the building.

Keywords:

Smoke potential, performance-based fire safety design, optical density, visibility, FDS

INTRODUCTION

After its introduction in 2004, performance-based analysis has been used for fire safety design of numerous buildings in Denmark. The fire safety design section in the Building Regulations [1] is fully performance-based, and the performance statements are deliberated upon in the guidance document 'Information om brandteknisk dimensionering' [2]. In order to facilitate the fire safety design for various non-standard buildings, a time comparison between the available safe egress time (ASET) and the required safe egress time (RSET) is established. There are four tenability criteria used for the ASET evaluation: 1) Smoke layer height, 2) Visibility, 3) Radiative heat flux in egress paths and 4) Temperature under the smoke layer. As the buildings are becoming more complex both from a geometrical and functional point of view, this type of comparison typically rely on numerical simulation methods, such as computational fluid dynamics (CFD), to assess the amount of heat and smoke produced during fires and to estimate the transport of the combustion products. In Denmark, Fire Dynamics Simulator (FDS) [3] has become the prevalent tool for calculation of the ASET, and the fire safety community has even created a best practice document for the use of FDS in performance-based fire design [4].

After the numerical simulation methods were adopted to simulate fires in buildings in Denmark, it has been observed that the optical properties of the smoke determine the time when critical conditions occur inside the building for a majority of cases with design fires located in large areas, such as atriums, concert halls, or auditoriums. [5]. In particular, these critical times are most often determined by the visibility criterion defined in the Danish guidance document for performance-based fire safety design [2]. The visibility criterion is essential for person safety because one of the most important negative effects of the smoke in respect to humans' behavior is represented by the obscuration of vision preventing the direct and logic escape, prior to fire spreading and the onset of directly critical conditions [6]. In addition, the walking speed during an evacuation scenario decreases proportionally with the decrease of the visibility level [7]. For this reason, the smoke production and transport topic presents a particular interest in fire safety strategies.

Moreover, numerical simulation methods are used to emulate the activation of the detection and alarm systems. In order to obtain a fast detection of an accidental fire, it is common for most buildings to use smoke detectors to perceive the presence of an accidental fire. Therefore, the quantity of smoke produced during fires and the physical and optical properties of the smoke determine the detection time, which is a component of the required safe egress time (RSET).

In the context of the time comparison used in performance-based design to determine the safety level of the building, it was observed that the physical and optical properties of the smoke produced during the combustion process determine, to a certain extent, both the available safe egress time (ASET) and the required safe egress time (RSET). Figure 1 is a schematic representation of how the smoke properties influence the time analysis used in performance-based fire safety design (PBFSD).

As there is no uniform test method to measure the optical properties of the smoke and in the absence of a best practice guide widely accepted by the fire engineering community, values from a vast variety of experiments are used in engineering analysis to express the properties that determine the decrease of visibility through smoke. Furthermore, it has been observed that the

selection of the smoke potential values, used as input in the numerical simulation models, to a high extent determine the results obtained using FDS Version 5 [3].

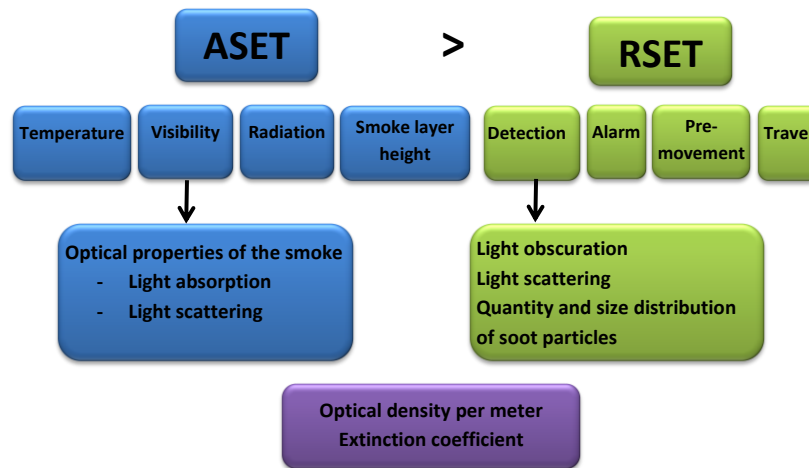


Figure 1 *Influence of smoke properties in performance-based analysis, where the requirement is that ASET exceeds RSET.*

Herein, the results of a parametric study that investigates the sensitivity of the input parameters related to visibility that are used for the numerical simulation used in the PBFSD are presented. The results are obtained using FDS 5, and the parametric study is applied in a case study involving a fire in an open plan office building.

CASE STUDY

In Denmark, the majority of performance-based analysis are conducted for buildings or building sections that, according to the Danish Building Regulations, cannot exceed the maximum area of 2000 m² and cannot have more than two stories for one fire section without undertaking further performance based fire engineering analysis [1]. These are typically atrium areas in office buildings, educational buildings, shopping centers, or hotels that connect all the floor levels of the building into one fire section. Therefore, the parametric study conducted as part of this investigation is based on a case study that implies a simplified model of a four-story office building with a central atrium that connects all floor levels into one open fire section.

Figure 2 offers a schematic representation of the building layout. The considered building model has a floor area of 800 m², while the atrium takes up to 100 m² at every floor level. In addition, the total height of the building is 14.0 m, and concrete slabs, with a thickness of 0.4 m, separate the floors. For the simplification of the building geometry, the model assumes that the building does not have suspended ceiling and the free height of the floor level is thus 3.2 m.

The building model represents an enclosure with small leakage areas at the floor level, as this ensures discharge of the pressure that is created in the building due to the thermal expansion of gases and the products generated during the combustion process. This limitation of the model is necessary to secure that the increasing pressure in the considered enclosure does not influence the smoke transport. Furthermore, due to the location of the openings, there is no smoke mass flow out of the building during the simulation period.

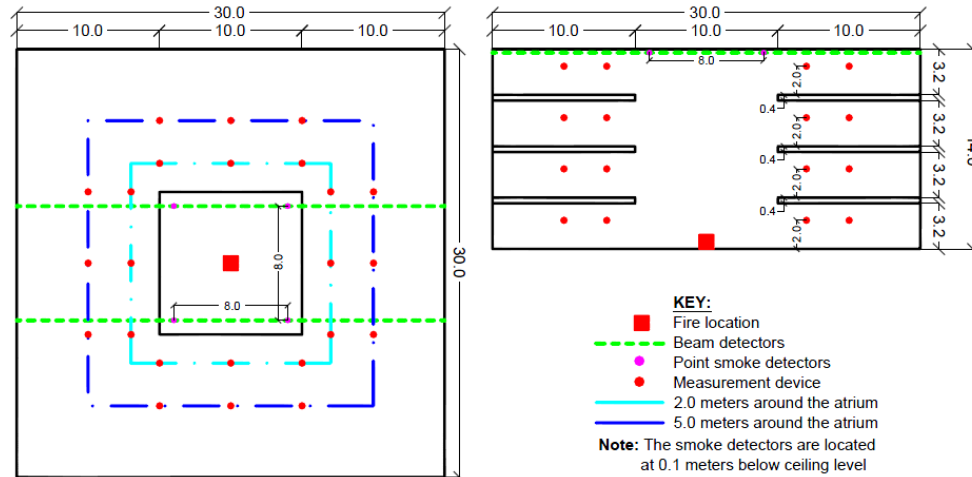


Figure 2 Top and side view of the office building geometry (all dimensions are in meters) with an overview of fire location of the installed detection systems.

Determining the Visibility Level and the Activation of Smoke Detectors

The detection of smoke is essential in performance based design because it enables activation of fire protection systems and thereby can be used to determine the initiation of evacuation procedures. Therefore, this study investigates the response sensitivity of two different detection systems, namely the beam detection system and the point smoke detectors (Heskestad ionization chamber).

Considering that this investigation aims to determine the sensitivity of numerical fire simulation in connection with the acceptance criteria for visibility and the response of smoke detectors, it is essential to determine the time when critical conditions occur inside the fire compartment and the time when different type of smoke detectors activate in relation to the optical properties of the smoke.

According to the Danish PBFSD guidance document [2], the optical density (per meter) should not exceed 1.0 dB/m at 2.0 m above the floor level in fire compartments with a floor area larger than 150 m². This corresponds to a visibility of approximately 10.0 m. For this reason, to measure the visibility level, 32 devices were placed at 2.0 m and 5.0 m around the atrium margins. Those devices measure the optical density at 2.0 m above the floor level and were set to activate when the optical density in the vicinity of the device decreases below the acceptance criteria; detection the time when critical conditions for occupant's safety occur within the building.

Fire Scenarios

The fire scenarios considered for this investigation imply the combustion of a single workstation located at the ground floor in the center of the atrium. This represents a realistic fire scenario for this type of building occupancy because office furniture, bookcases, computers, books, paper and other combustible materials located in the office area represent the main fuel source in offices. Moreover, because the research focuses mainly on the production parameters that influence visibility and detection time, while detailed smoke transportation is secondary, the location of the fire does not represent an important factor herein. Actually, locating the fire in the central of the

atrium is beneficial for this research because it minimizes the influence of the smoke transport on the results.

The considered scenarios rely on the combustion parameters of a single workstation fire obtained experimentally by the National Institute of Standards and Technology for a generic workstation [8]. Table 1 presents the characteristics of the office fire that constitutes the basis of this investigation.

Table 1 Key results from single workstation fire tests.

Workstation	
Peak heat release rate [kW]	8480
Peak mass loss rate [kg/s]	0.308
Total mass loss [kg]	205.0
Time to peak [s]	530
Effective heat of combustion [kJ/g]	19.8

This investigation considered a αt^2 fire [9, 10]. Different growth rates were investigated for the fire scenario described above to validate the results of the study for different growth rates of the fire [11]. Beside the fact that this fire scenario is representative for office occupancies the size of the fire ensures that critical conditions occur at all floor levels and for all the growth rates considered during this research.

NUMERICAL SIMULATION

In Denmark, FDS is widely used in performance based design in order to assess, among other parameters, the visibility level inside buildings and to determine the activation time of the smoke detectors. Therefore, it is of primarily importance for the parametric study performed during this investigation to identify the optical and physical properties of the smoke that influence both visibility and activation of smoke detectors.

By analyzing the numerical model used by FDS to determine the visibility level in enclosures, it was determined that the visibility is calculated in each mesh cell based on the light extinction coefficient, which express the reduction of the light intensity in accordance with Bouguer's law (also known as Lambert-Beer law) [6, 12]. The light extinction coefficient is further defined as the product of the mass extinction coefficient of the soot and the concentration of soot particles in the gaseous phase. Equation 1 gives the mathematical expression of Bouguer's law, which is used in FDS to determine the reduction of light intensity associated with the optical properties of the smoke [13].

$$I = I_0 \exp(-K_s M_s L) \quad (1)$$

Here, I is the reduced light intensity [cd], I_0 the initial light intensity [cd], K_s the mass specific extinction coefficient [m^2/g], M_s the mass concentration of soot particles [g/m^3] and L is the path length of the optical density passing through the smoke [m].

An investigation of the numerical model used in FDS to emulate the activation of the smoke detectors showed that the response of the smoke detectors is also determined based on the obscuration of light, both for beam detectors and point smoke detectors. As mentioned, the obscuration of light is further determined based on the mass extinction coefficient of the soot and the concentration of soot particles in the gaseous phase. The mass specific extinction coefficient of soot has been determined experimentally, and it was found to be $8.7 \pm 1.1 \text{ m}^2/\text{g}$ for post-flame generated smoke [14]. The value is smaller, around $4.4 \text{ m}^2/\text{g}$, and varies more for smoke produced during pyrolysis of materials [15]. The smaller value is a consequence of the reduction of the light absorbance effect of soot particles. Considering this, it is clear that the mass

concentration of soot particle in the gaseous phase determine the results of numerical fire simulations for both visibility and activation of smoke detectors.

Furthermore, it was determined based on the combustion model in FDS that the optical properties of the smoke, or more precisely, the mass concentration of soot particles, are determined by the quantity of carbon particles released during the combustion process. A detailed analysis of the chemical reaction that governs the combustion process shows that the quantity of carbon particles produced during fires is primarily determined by the heat of combustion and soot yield. In addition, the investigation also considered other FDS input parameters, precisely the mesh size and fuel chemical formula, as possible parameters that influence the results of the parametric study. The investigation showed that the results of the study were independent in respect to the different mesh sizes and chemical formulas of the fuel [11]. Therefore, the heat of combustion and soot yield were the input parameters considered as variables for the parametric study.

It should be noted that the soot yield used in the numerical simulation environment to describe the optical properties of the smoke is further expressed as smoke particle potential (D_0). The smoke particle potential represents the parameter used in different experimental research to express the optical properties of smoke in relation to the mass of fuel consumed. The following equation reflects the correlation between the two parameters [16].

$$D_0 = \frac{POD \cdot y_s}{0.2303} \left[\text{dB} \cdot \frac{\text{m}^2}{\text{g}} \right] \quad (2)$$

y_s is the yield of soot [$\text{g}_{\text{soot}}/\text{g}_{\text{fuel}}$] and POD is the particulate optical density [m^2/g] (equivalent to the mass specific extinction coefficient). $POD=8.7 \text{ m}^2/\text{g}$ for flaming combustion [16].

STATISTICAL DETERMINATION OF THE INPUT PARAMETERS

As mentioned, the effective heat of combustion and the smoke potential represent the most important combustion parameters that determine the smoke production and its optical properties. Therefore, for the purpose of this study, it is important to determine the most representative values for these parameters and use them as input values for the parametric study. In order to determine feasible values for smoke potential and heat of combustion for office building fires, a statistical approach is used in the following.

Smoke Potential for Office Building Materials

Considering that this investigation is conducted on a case study of an office building fire, it is important to investigate the potential to produce smoke of materials and furniture elements usually found in office buildings. In addition, this research intends to present a range of smoke potential values that characterizes fires in office buildings, rather than impose parameters that are to be used in office fires simulations. For this reason, the research collects data from different experiments and converts it in smoke potential unit in order to constitute a database of smoke potentials for office buildings.

The statistical method is used to determine the smoke potential values used as input for the parametric study because it has been observed that there is no uniform test method to measure

the optical properties of the smoke. In addition, it was observed that different smoke potential values are registered for similar material or furniture element during different tests. For example, using the National Bureau of Standards smoke test (NBS test) [6], the smoke potential of a hardboard was determined to be $0.35 \text{ ob}\cdot\text{m}^3/\text{g}$, while using the smoke test developed in the Fire Safety Engineering Department at Edinburgh University [13], the smoke potential of the same object was determined to be $0.11 \text{ ob}\cdot\text{m}^3/\text{g}$.

Because the collected dataset presents a high degree of variation, it is subdivided into intervals of $0.1 \text{ ob}\cdot\text{m}^3/\text{g}$ and represented graphically using the histogram displayed in Figure 3. The histogram representation is introduced as a means of visual characterization of the collected dataset. It is also a useful tool to reduce the data to a manageable form suitable for further analysis. Another type of representation of the dataset renders the cumulative frequency distribution, as presented in Figure 4, by summing up the frequency for each interval in increasing order. This type of representation provides a useful tool for selecting the most representative smoke potential values for the considered cases.

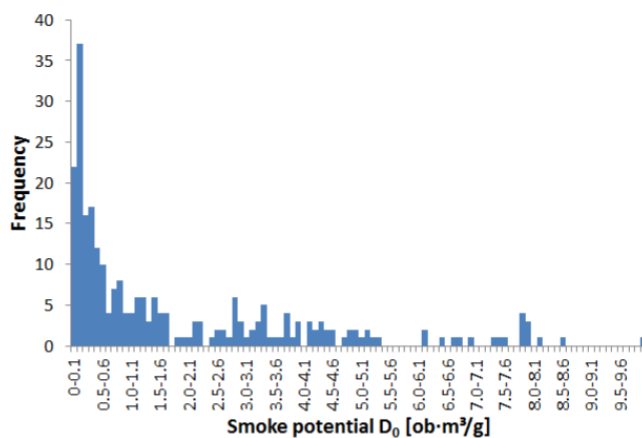


Figure 3 Histogram representation of the literature values of smoke potential for office building materials [6, 13, 17, 18, 19].

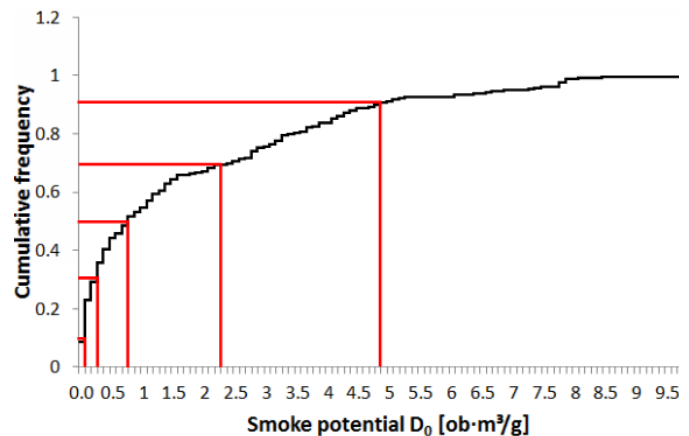


Figure 4 Cumulative distribution function of the literature values of smoke potential for office building materials.

The analysis of the dataset shows that the values of the smoke potential for office building materials take on values between $0.0 \text{ ob}\cdot\text{m}^3/\text{g}$ and $10.0 \text{ ob}\cdot\text{m}^3/\text{g}$, and the larger number of values is found towards the lower end of the interval. More than 90% of the smoke potential values are in the first half of the interval. Furthermore, it can be stated with high certitude that for the fire scenario considered herein, the smoke potential of the fire may take one of the values contained in the 80 percent interval comprised between 0.2 and $4.9 \text{ ob}\cdot\text{m}^3/\text{g}$. For further analysis, the following smoke potential values are selected for the sensitivity analysis performed during this investigation: i) 10th percentile - $0.2 \text{ ob}\cdot\text{m}^3/\text{g}$, ii) 30th percentile - $0.4 \text{ ob}\cdot\text{m}^3/\text{g}$, iii) 50th percentile - $0.9 \text{ ob}\cdot\text{m}^3/\text{g}$, iv) 70th percentile - $2.3 \text{ ob}\cdot\text{m}^3/\text{g}$ and v) 90th percentile - $4.9 \text{ ob}\cdot\text{m}^3/\text{g}$.

Effective Heat of Combustion for Office Building Materials

The effective heat of combustion represents the second parameter that influences visibility and the activation of smoke detectors because it determines the quantity of smoke produced during the combustion process. Therefore, it is important to take into account this property of the materials and furniture elements considered for the smoke potential database.

The effective heat of combustion can be determined experimentally or calculated from the complete heat of combustion, providing that only the complete heat of combustion was experimentally determined using a bomb calorimeter. This is not the case of real fires, during which the combustion efficiency of the materials that produce sooty flames is generally lower, approximately 60-70% of the complete heat of combustion [20]. Furthermore, the most representative values for the effective heat of combustion of office fires are selected as the marginal and central values of the 80th percentile.

The following three heat of combustion values are selected as representative for the collected data and are further used as input for the sensitivity analysis performed in the following: i) 10th percentile - 7.0 kJ/g, ii) 50th percentile - 15.0 kJ/g and iii) 90th percentile - 26.0 kJ/g.

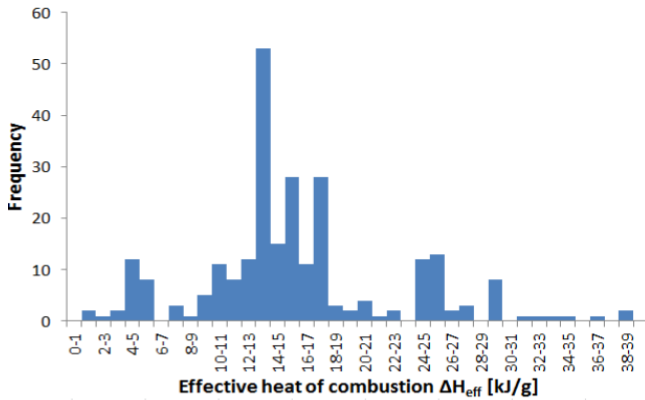


Figure 5 Histogram representation of the effective heat of combustion for office building materials [17,19]

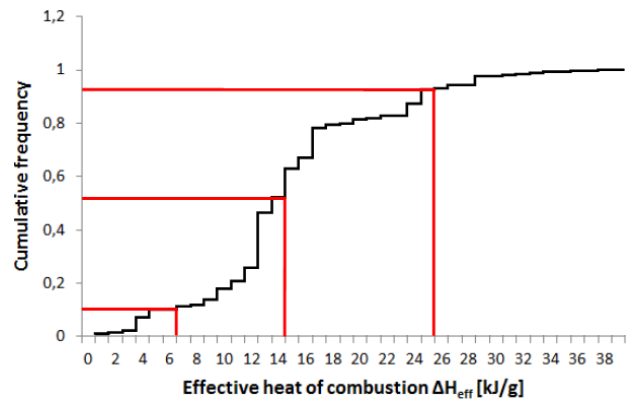


Figure 6 Cumulative distribution function of the heat of combustion for office building materials.

RESULTS AND DISCUSSION

The results of the parametric study performed as part of this investigation are graphically presented in order to determine the correlation between visibility and smoke detectors response and the parameters that determine the optical properties of the smoke, namely the smoke potential and the effective heat of combustion.

Visibility Criteria

As described, the visibility level at 2.0 m above each floor level represents one of the criteria for the occupant safety in buildings, which further determines the available safety egress time (ASET). The time until untenable conditions occur (based on the visibility criterion) is referred to as $t_{critical}$.

Figure 7 presents the time until untenable conditions occur in the building based on the visibility criteria at third level (top floor) in relation to the simulation inputs used to define the smoke production. The graphical representation of the parametric study results includes three data sets corresponding to the representative heat of combustion for office building fires determined based on the statistical approach presented in the previous section. Moreover, each of the three data sets contains $t_{critical}$ for the five smoke potential values considered representative for this case study. As such, Figure 7 presents results from 15 FDS runs. By looking carefully at $t_{critical}$ and the parameters used in FDS to define the combustion process, it can be observed that for fires defined by smoke potential values smaller than 2.0 $ob \cdot m^3/g$, the values registered for $t_{critical}$ are highly influenced by the selection of the smoke potential value. In these cases, $t_{critical}$ increases

exponentially with the reduction of the smoke potential value used in the simulations. Moreover, it can be observed that for smoke potential values higher than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$, the time when critical conditions occur inside the building tends to converge to a constant value equal to the smoke layer descending time. The smoke layer descending time was determined using a theoretical formula to determine the smoke layer descending time for atriums [21]. Moreover, for the same smoke potential value, the quantity of smoke produced during the combustion process, as determined by the heat of combustion, influences t_{critical} to a high degree. In other words, if the heat of combustion is higher, then the fire produces less smoke. Therefore, it requires a longer accumulation period to reach the visibility criteria limit. Finally, it should be noted that similar results were registered at the lower levels of the building and therefore the relation between t_{critical} and the input parameters that determine the optical properties of the smoke is independent of the floor level, as should be.

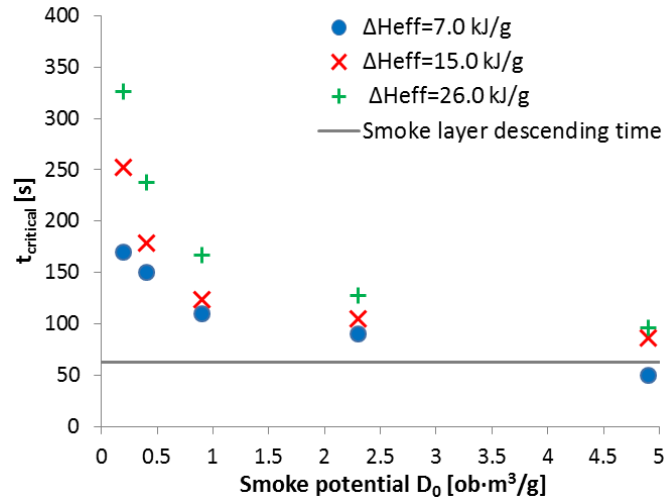


Figure 7 Time to critical conditions on the third level (top floor) of the office building.

Smoke Detection

The second central objective of this investigation was to determine the sensitivity of the smoke detectors with regard to the optical properties of the smoke. To accomplish this, the activation time of two smoke detection systems or, more precisely, the beam detection system and the point smoke detectors, was registered for the each FDS run in the case study and plotted against the smoke potential value used in the simulation. Furthermore, different plots are used to represent the heat of combustion influence on the detectors activation time.

Figure 8 and Figure 9 show the activation time of the beam detection systems and point smoke detectors in relation to the simulation inputs used to define the smoke production, respectively. The results of the parametric investigation are graphically represented in a similar manner as for the visibility criteria (Figure 7). In addition, each graph offers a representation of the transport time of the smoke analytically determined using the Heskestad plume equation for the velocity in the plume centerline and the ceiling jet theory and the maximum velocity equation [22, 23].

Comparing the activation time of the smoke detectors to the smoke potential values used as input data in FDS, it can be observed that the detection time converge asymptotically to the transport time for smoke particle potentials higher than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$. This occurs despite the fact that the detection principles of the two systems are based on different phenomena and different activation threshold values. In other words, for high smoke potential values, the activation time of the detectors is mainly determined by the smoke transport time and it is independent of the smoke potential value used as input for the combustion model in FDS. Moreover, in this case the effective heat of combustion of the fire does not influence the activation time of the detectors. This means that the quantity of soot particles produced during the combustion process is

sufficient to determine the activation of the detectors regardless of the values of the effective heat of combustion used in the simulation. However, only a small proportion, approximately 30%, of the materials and furniture elements in office buildings are characterized by a smoke potential higher than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$. This section of the materials database primarily consists of solid plastics, thermoplastic polymers and halogenated materials. The most representative examples are polyurethane foams, polystyrene foams, polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), acrylonitrile butadiene styrene (ABS) and silicon rubbers [11].

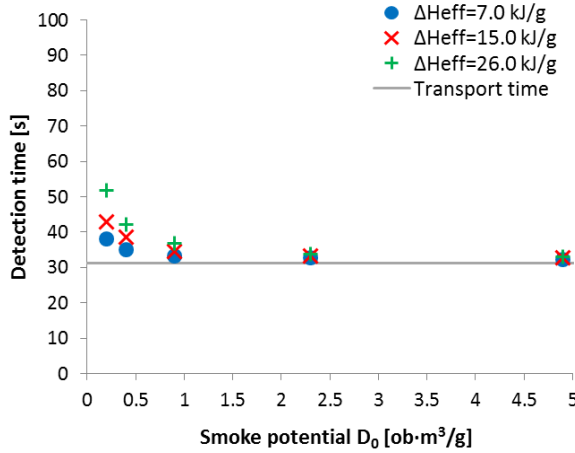


Figure 8 Activation time of beam detectors

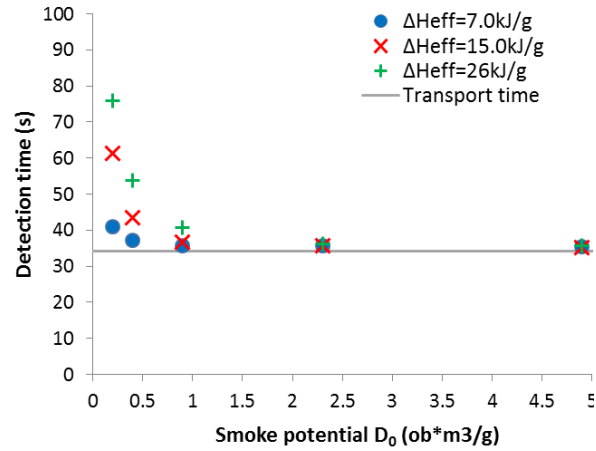


Figure 9 Activation time of point smoke detectors

For smoke particle potentials smaller than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$, on the other hand, the selection of the value used in fire simulation to describe the optical properties of the smoke determines to a high extent the response of the detectors. In this case, it can be observed that the effective heat of combustion used as input to define the combustion process has a strong influence on the detectors' activation time. Furthermore, it is clear that the soot accumulation phenomenon has the highest influence on the detectors activation time for small smoke potential values, whereas the transport time has only a secondary role. A majority of the natural and cellulosic materials, as well as most of the furniture elements, considered as possible fuels during office building fires have a smoke potential value lower than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$. Therefore, it is highly relevant in performance based fire design to determine the correlation between the detectors' response and the two properties used to define the smoke production.

It is not straightforward to derive an analytical correlation between the detectors activation time and the properties used to define the combustion process and soot production in FDS, because the mass concentration of soot particles in the vicinity of the detector is determined by the smoke transport phenomenon and the soot particles accumulation at the ceiling level, as well as by the combustion process itself. Therefore, the graphical representation of the detectors response in relation to the combustion parameters, as illustrated in Figure 8 and Figure 9, is deemed suitable for use in performance based design in order to evaluate the detectors' activation time based on the simulation input parameters and the transport time.

Moreover, the graphical representation of the results from the parametric study shows that the beam detectors system response is less sensitive to the smoke potential and heat of combustion values in comparison to the point smoke detectors. This is caused by the fact that the two systems investigated during this parametric study have different activation set points. In order to

compare the detectors response, their activation threshold value is converted into extinction coefficient units. Table 2 presents the detectors' activation set point expressed in optical density unit.

Table 2 *Conversion table for the detectors' activation set point*

	Beam detector	Point smoke detectors
Activation set point	$O=30$ [%]	$O_u=4.0$ [%/m]
Length [m]	30	-
Optical density per meter [1/m]	0.012	0.041

In order to ensure the required evacuation safety level ($ESL=ASET/RSET > 1$), it is essential in the design process to estimate the activation time of the detectors based on their activation set point and the combustion parameters, or to determine the activation threshold value of the detectors in order to obtain the desired detection time. This graphical representation of the results of this parametric investigation provide a design method to estimate the detection time or the required activation set point of the smoke detectors based on the properties that characterize the combustion process, namely the smoke potential and the effective heat of combustion, and the transport time.

CONCLUSION

This parametric investigation shows that fire safety performance-based analysis based on numerical simulation methods, such as FDS fire simulations, are sensitive to the selection of the input parameters that control the optical properties of the smoke, namely the heat of combustion and the smoke potential, if the combustible materials are characterized by smoke potential values lower than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$. The selection of the input parameters is relevant for typical building fires, such as the office building considered herein, because approximately 70% of the building materials and furniture elements considered as potential combustible materials are characterized by smoke potential values lower than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$. Moreover, this study shows that the results of the time comparison used in the design phase to establish the evacuation safety level (ESL) of the building is determined by the selection of the input parameters, which influence both the available safe egress time (ASET) and the required safe egress time (RSET).

The sensitivity of the numerical fire simulations need to be considered in the design process in order to provide a solution that will ensure the safe evacuation of all occupants. The current level of the fire research offers sufficient information and methods to allow engineers to estimate the heat of combustion for different design fires in buildings. In contrast, the estimation of the smoke potential values that characterize the design fires is more challenging, especially for composite combustible materials, as there is no uniform test method to measure the smoke potential. Therefore, the engineers rely on values from different experiments to estimate the optical properties of the smoke. Moreover, as the majority of combustible materials in buildings are characterized by smoke potential values lower than $2.0 \text{ ob}\cdot\text{m}^3/\text{g}$, the underestimation of this input parameter may lead to the wrong assessment of the evacuation safety level of the building. In this context, in order to ensure a robust fire safety solution it is recommended that values around $1.0 - 2.0 \text{ ob}\cdot\text{m}^3/\text{g}$ are used to define the optical properties of the smoke in office building fires. Using these values to defining the design fires will reduce the sensitivity of the numerical fire simulation and further reduce the risk of overestimating the evacuation safety level (ESL) of the building.

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